hexanes as the eluant afforded 0.1468 g (72%) of lactam selenide **39**. Mor polar epimer: NMR δ (CCl_4) 7.80–7.10 (5 H, m), 4.50–4.00 (1 H, m), 3.80–3.60 (10 H m, containing 2 s at 3.72 (3 H) and 3.70 (6 H), 3.40 (2 H, m), 2.45 (2 H, m), 2.10 (3 H, s), 0.90 (9 H, s), 0.05 (6 H, s); IR ($CHCl_3$) ν_{max} 1690 cm^{-1}. Less polar epimer: NMR δ (CCl_4) 7.80–7.10 (5 H, m), 4.25 (2 H, m), 3.80–3.60 (12 H, m, containing 2 s at 3.79 (3 H) and 3.72 (6 H), 3.30–2.50 (2 H, m), 2.13 (3 H, s), 0.90 (9 H, s), 0.05 (3 H, s), 0.04 (3 H, 5); IR ($CHCl_3$) ν_{max} 1690 cm^{-1}. Mixture of epimers: mass spectrum *m/e* 577 (P), calcd for $C_{28}H_{39}NO_5SeSi$ 577.1763, found 577.1771.

(9*R,9a*S**)-9-[(*tert*-Butyldimethylsiloxy)methyl]-2,3,9,9a-tetrahydro-5,7,8-trimethoxy-6-methyl-2-(phenylselenyl)-1*H*-pyrrolo[1,2-*a*]indole (40).** To a solution of **39** (0.1257 g, 0.217 mmol) in 6 mL of anhydrous THF was added 0.9 mL of 1 M BH_3–THF dropwise. The solution was then heated under reflux for 60 min, cooled with an ice bath, quenched with 1 mL of 10% aqueous H_2SO_4, and neutralized with 3 mL of 10% aqueous KOH, and most of the THF was evaporated in vacuo at room temperature. The residual solution was extracted thoroughly with ether. The combined organic layers were washed with brine and dried ($MgSO_4$). The volatiles were evaporated in vacuo, and the residue was chromatographed on 10 g of silica gel. Elution with 33% ethyl acetate in hexanes afforded 0.1014 g (83%) of amine **40**: NMR δ (CCl_4) 7.70–7.10 (5 H, m), 4.30–3.10 (15 H, m, containing 2 s (3 H each) at 3.70 and 3.59), 2.20–1.80 (5 H, m), 0.90 (4.5 H, s), 0.87 (4.5 H, s), 0.05 (6 H, m); IR ($CHCl_3$) ν_{max} 2930, 2850 cm^{-1}; mass spectrum *m/e* 563 (P).

(9*R,9a*S**)-[(*tert*-Butyldimethylsiloxy)methyl]-9,9a-dihydro-5,7,8-trimethoxy-6-methyl-3*H*-pyrrolo[1,2-*a*]indole (41).** To a solution of **40** (85.8 mg, 0.152 mmol) in 0.8 mL of THF at 0 °C was added 30% H_2O_2 (15.5 μL, 0.152 mmol). After the mixture was stirred for 60 min the reaction was warmed to room temperature, and 20 mg of $NaHCO_3$ was added. Stirring was continued for 60 min. The mixture was quenched with 100 μL of saturated $Na_2S_2O_3$, and most of the THF was evaporated at room temperature in vacuo. The residual mixture was diluted with ether and saturated $NaHCO_3$. The organic layer was washed with brine and dried ($MgSO_4$). Concentration in vacuo at room temperature and chromatography of the residue on alumina (activity grade 1) with 11% ethyl acetate in hexanes as the eluant afforded 33.8 mg (55%) of olefin **41**: NMR δ ($CDCl_3$) 5.82 (2 H, s), 4.80 (1 H, m), 4.20–4.00 (3 H, m), 3.84 (3 H, s), 3.81 (3 H, s), 3.77 (3 H, s), 3.57 (2 H, m), 2.17 (3 H, s), 0.93 (9 H, s), 0.12 (3 H, s), 0.09 (3 H, s); IR ($CHCl_3$) ν_{max} 2930, 2850 cm^{-1}; mass spectrum, *m/e* 405 (P), calcd for $C_{22}H_{35}NO_4Si$ 405.2335, found 405.2313.

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Registry No. **6**, 19676-67-6; **7**, 79421-11-7; **8**, 79421-12-8; **9**, 65480-96-8; **10**, 65480-97-9; **11b**, 65481-00-7; **13**, 65481-02-9; **14**, 65481-03-0; **15**, 65481-04-1; **16**, 79465-33-1; **17**, 79465-34-2; **24**, 79421-13-9; **25**, 79421-14-0; **33**, 79421-15-1; **34**, 79421-16-2; **36**, 79421-17-3; **37**, 79421-18-4; **38** (isomer 1), 79435-69-1; **38** (isomer 2), 79465-96-6; **39** (isomer 1), 79421-19-5; **39** (isomer 2), 79465-35-3; **40**, 79421-20-8; **41**, 79421-21-9; *trans*-1,4-dichlorobut-2-ene, 110-57-6; (carbomethoxy)acetyl chloride, 37517-81-0.

Decomposition of *endo*- and *exo*-(2-Norbornyl)formyl *p*-Chlorobenzoyl Peroxides

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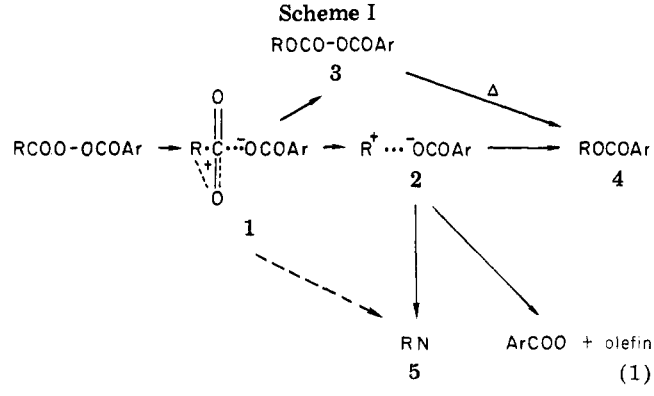
The subject peroxides undergo first-order decomposition in several solvents with rates increasing moderately with solvent polarity and endo/exo rates in a ratio of 1:10–100. Carboxyl inversion product, ROCOOCOAr, and other "polar" products are formed with no evidence for significant free-radical production. Products from an *exo*-peroxide have exclusively exo configurations, but carboxyl inversion product from endo peroxide contains small amounts of exo isomer. In acetic acid, 2-norbornyl acetate is a major product, with an endo/exo ratio of 14:86 from the *endo*-peroxide. Optically active *exo*-peroxide in acetic acid gives *exo*-2-norbornyl acetate with 6% net retention of configuration. The results are discussed in terms of successive ion pairs and carboxyl inversion product arising early on the reaction path and other products later.

Diacyl peroxides, RCO–O_2–COAr [R = *sec*- or *tert*-alkyl or benzyl and Ar = negatively substituted phenyl group (*m*-ClPh has been most investigated)], undergo a relatively rapid first-order decomposition, with little or no evidence for free-radical production.[1-5] In inert solvents the major product is usually the carboxyl inversion product or mixed aroyl carbonic anhydride (RO–CO–O–COAr), but ester (ROCOAr) or acid (ArCOOH) plus olefin may be formed as well.[6] In nucleophilic solvents, solvent is captured, e.g., to yield imides ($CH_3CONRCOAr$)[2,5] in acetonitrile, acetate esters[5] ($ROCOCH_3$) in acetic acid, and ethers or alcohol (ROH) in the presence of alcohols[5] or water.[4]

Scheme I



The reactions increase moderately in rate with solvent ionizing power and are generally considered to involve ion-pair intermediates. A plausible formulation is as shown in Scheme I.

(1) Denney, D. B.; Sherman, N. *J. Org. Chem.* **1965**, *30*, 3760–3761.
(2) Walling, C.; Waits, H. P.; Milovanovic, J.; Pappiaonnou, C. G. *J. Am. Chem. Soc.* **1970**, *92*, 4927–4932.
(3) Taylor, K. G.; Gorindan, C. K.; Kaelin, M. S. *J. Am. Chem. Soc.* **1979**, *101*, 2091–2099.
(4) Linhardt, R. J.; Murr, B. L. *Tetrahedron Lett.* **1979**, 1007–1010.
(5) Walling, C.; Sloan, J. P. *J. Am. Chem. Soc.* **1979**, *101*, 7679–7683.
(6) Such products, along with varying amounts of radical products, are, in general, observed in peroxides showing "two-bond" scission. For a general discussion see: Koenig, T. In "Free Radicals"; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. 1, pp 136–137. It has been proposed that both radical and ionic products are produced through a common rate-determining transition state.[2]

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Table I. Decomposition Rates of Peroxides $RC(O)OOC(O)C_6H_4$-*m*-Cl(m)

	10^4k, s^{-1} (40 °C)				
	R = 2-norbornyl		R = 4-*tert*-butylcyclohexyl		R =
solvent	endo	exo	cis	trans	2-butyl
cyclohexane	0.027	0.24	4.4	3.9	0.60
CH_3CN	0.64	77.0	59.0	42.0	17.2
CH_3COOH	0.43	6.0			16.0
2-butanol	0.26	2.7	44.0	28.0	9.0

The timing of the different steps is of considerable interest and has been studied most effectively by following the stereochemistry of the products where the CO of the aliphatic moiety of the peroxide is attached to a suitable center. The carboxyl inversion product **3** is generally formed with complete retention of configuration as is any ester (**4**) produced by its thermal decomposition.[6,7] On the other hand, ester arising from later ion pars (**3**) shows only a small retention of its original configuration.[8]

In Scheme I, N: represents a nucleophilic solvent and RN the products resulting from its reaction with intermediate ion pairs. In the case of R = *sec*-butyl we have shown that, in both acetonitrile and acetic acid, such products are formed with approximately 14% net inversion. With R = 4-*tert*-butylcyclohexyl the situation is less clear, but both isomers give predominantly trans products.[5] All these results imply that reaction with nucleophilic solvent, like collapse to an ester, occurs from looser ion pairs at a later stage in the reaction than does formation of the carboxyl inversion product.

This paper reports a similar study of *endo*- and *exo*-2-norbornylformyl *m*-chlorobenzoyl peroxides in which the behavior of intermediate ion pairs derived by other reaction paths has received such exhaustive investigation.[9]

Results

endo- and *exo*-2-norbornyl carboxylic acids were prepared by literature methods and converted to the peroxides by reaction of their acid chlorides with *m*-chloroperoxybenzoic acid. Decomposition rates in several solvents were followed by iodometric titration and gave good first-order plots. The more rapid decomposition of the *exo*-peroxide in acetonitrile was followed by IR spectrometry. Results are listed in Table I, together with literature data on some related peroxides for later discussion. Results of product analyses are summarized in Table II. Yields of carbonyl-containing products in several solvents were estimated from IR spectra of the solutions after the reaction. ROH (norborneol) was determined by gas chromatography (GC) and is not a primary product. In nonprotonic solvents we have previously concluded that it is formed by pyrolysis of the carboxyl inversion product during analysis and thus reflects its stereochemistry. In acetic acid it is formed rapidly by reaction of the carboxyl inversion product with solvent.[5]

Table II. Decomposition Products of (2-Norbornyl)formyl *m*-chlorbenzoyl Peroxides

		from endo peroxide		from exo peroxide,
solvent	products[a]	yield, %	endo/exo ratio	yield, %
cyclohexane	ROH[b]	33	98:2	*e*
	ROCOAr	25		
	ROCOOCOOAr	42		64
	ArCOOH	13		33
CCl_4	ROH[b]	39	100:0	14[e]
	ROCOAr			
	ROCOOCOAr	58		68
	ArCOOH	49[c]		49[c]
CH_3CN	ROH[b]	35	99:1	12[e]
	ROCOAr			
	ROCOOCOAr	41		42
	$RN(COCH_3)COAr$	16		25
CH_3COOH	ROH[b]	*d*	81:19	*d*, *e*
	$ROCOCH_3$	*d*	14:86	*d*, *e*
2-butanol	ROH[b]	49	98:2	14[e]
	ROCOOCOAr			9
	ArCOOH			25

[a] R = 2-norbornyl, Ar = *m*-chlorophenyl. [b] Derived from ROCOOCOAr; see text. [c] May include some RCOOH. [d] Yields not determined, but ROH/$RCOOCH_3$ ratio is 32:68 (endo) and 22:78 (exo). [e] The endo/exo ratio was 0:100.

In acetic acid IR analysis was not possible, and norborneols and norbornyl acetates were the only products detected by GC. Since the *endo*- and *exo*-acetates could not be resolved by GC, the mixture of acetates was isolated by thin-layer chromatography (TLC) and hydrolyzed with base, and the endo/exo ratio of the resulting alcohols was determined by GC.

In addition to the results in Table II, we have also determined the stereochemistry of the norbornyl acetate obtained by decomposing optically active *exo*-peroxide in acetic acid. The peroxide, derived from (*S*)-(+)-*exo*-2-norbornanecarboxylic acid (89.0% ee), yielded (*S*)-(+)-*exo*-norbornyl acetate (5.44% ee), corresponding to 6.12% net retention of configuration.

Discussion

Qualitatively, our results parallel those observed with peroxides of similar structure, but quantitatively, particularly in regard to stereochemistry, they lead to some new conclusions about the timing of various product-forming steps. From Table I, decomposition rates increase moderately with solvent polarity, somewhat over 20-fold in going from cyclohexane to acetic acid. The only anomaly is the high rate for the *exo*-peroxide in acetonitrile. Although the value of the rate constant is of lower precision because of the different analytical method employed, we believe the high rate is real and have no good explanation.

In all solvents, *exo*-peroxide decomposes more rapidly than *endo*-peroxide by a factor of 10–100. Since the rate difference in a typical solvolysis is 350 (or 1550 on allowing for internal return),[9] both this and the small solvent dependence indicates a rate-determining transition state in which C-2 of the norbornane skeleton has developed relatively little positive charge. Further, the actual rates of decomposition of even the exo isomer are, in general, lower than those of the other peroxides in Table I, where R is also a secondary alkyl radical, suggesting no marked stabilization of the exo transition state.[10]

(7) Carboxy inversion products decompose to esters on prolonged heating, and these were the major products reported in early studies. The first observation of retention of configuration in this sort of reaction was by: Kharasch, M. S.; Kuderna, J.; Nudenberg, W. *J. Org. Chem.* **1954**, *19*, 1283. The synthetic utility of the method for converting acids to alcohols was pointed out by Denney.[1]

(8) It is sometimes difficult to distinguish the two paths of ester formation, but a particularly clean-cut case is provided where R = *p*-methylbenzyhydryl. Here, in CH_2Cl_2–ether, the ester (14% net retention) is the major product under conditions where the carboxyl inversion product is stable. At higher temperatures the latter decomposes to the ester with >90% retention.[4]

(9) For a current review of the 2-norbornyl cation problem, cf.: Lowry, T. H.; Richardson, K. S. "Mechanism and Theory in Organic Chemistry", 2nd ed.; Harper and Row: New York, 1981; pp 413–428.

The products listed in Table II also parallel those which we and others have reported previously. As judged by the composition of the 2-norborneols obtained on its decomposition, the carboxyl inversion product from the *exo*-peroxide is formed with complete retention of configuration as has been observed in most previous cases. However, the reaction of the *endo*-peroxide is not as clean-cut, and it too yields some *exo*-alcohol, particularly in acetic acid. Partial loss of stereochemistry has also been observed in the carboxyl inversion products from a peroxide in which R = 4-*tert*-butylcyclohexyl,[3] cyclobutyl,[5] and cyclopropylmethyl,[5] and the observations require that the formation of carboxyl inversion product is not some sort of concerted rearrangement but, in fact, involves an ion pair as in Scheme I with a long enough life for rearrangement when sufficient driving force is present.

The stereochemistry of the 2-norbornyl acetates obtained in acetic acid from nucleophilic attack by solvent is also a bit surprising. As expected, *exo*-peroxide gives solely *exo*-acetate. However, with *endo*-peroxide the exo/endo ratio is only 86:14. Since the universal rule for solvolyses seems to be that endo and exo starting materials give solely exo products, the intermediate which reacts with acetic acid is not entirely the simple ion pair **2** in Scheme I. A similar conclusion follows from our results with the optically active *exo*-peroxide. Again, contrary to the solvolysis rule of complete racemization, acetate is formed with small (6%) net retention. Both results indicate that some acetate must arise early in the reaction from species other than the ion pair **2**. It is noteworthy that very similar results were observed by Berson in the diazotization of *endo*- and *exo*-2-norbornylamine in acetic acid. *endo*-Amine gave about 95% exo products and optically active *exo*-amine shows about 11% retention of configuration.[11]

In summary, while our results are in general consistent with Scheme I and the idea that carboxyl inversion product arises early and other products later along the reaction path for decomposition of this class of peroxides, our stereochemical results suggest that there is some overlap in the timing of the two processes and that the ion pairs postulated as intermediates cannot be entirely equivalent to those involved in solvolyses.

Experimental Section

Preparation of Peroxides. Intermediate *endo*- and *exo*-norbornane-2-carboxylic acids were prepared by literature methods. The mixed *endo*- and *exo*-5-norbornene-2-carboxylic acids obtained by Diels–Alder condensation of acrylic acid and cyclopentadiene[2] were separated by converting the former to the iodo lactone and subsequent regeneration by treatment with Zn in acetic acid.[13] The separated acids were then hydrogenated to the norbornane-2-carboxylic acids by using either platinum oxide or palladium on charcoal:[14] mp (endo) 64.4–65 °C, mp (exo) 55.5–56.5 °C. Optically active exo acid was obtained by resolution of a portion of the *exo*-5-norbornenecarboxylic acid by recrystallization of its cinchonidine salt.[14] The final product had $[\alpha]_D$ 34.7° in 95% ethanol, corresponding to (*S*)-(+)-2-norbornanecarboxylic acid of 89% optical purity. The endo and exo acids were converted to their chlorides and then to the peroxides by reaction with *m*-chloroperoxybenzoic acid in pyridine–pentane at −5 to −20 °C.[5] The final peroxides were liquids with the expected NMR and IR spectra, and their purity was established by iodometric titration.

Reference Materials. Authentic samples of *endo*- and *exo*-2-norborneols, 2-norbornyl acetates, and 2-norbornyl *m*-chlorobenzoates were purchased or prepared by standard literature methods.

Kinetic experiments were carried out under N_2 on 0.05–0.07 M solutions of the peroxides in the solvents listed in Table I by using 2.0-mL samples in screw-capped test tubes placed in a 40 °C thermostat. After appropriate times the samples were removed and quenched in dry ice–isopropyl alcohol, and the remaining peroxide was determined by iodometric titration. All runs gave good first-order plots, with standard deviations of the rate constants of <3% (from the scatter of the experimental points). The decomposition of *exo*-peroxide in acetonitrile was too rapid for this technique, so it was followed by IR spectrometry, and the resulting rate constant is probably of lower precision.

Product Analyses. The yields of carboxyl inversion product, imide, and acid in Table II were estimated from IR spectra of reaction mixtures by using the intensities of peaks at 1790–1803, 1722, 1661, and 1598–1700 cm^{-1}, respectively, and ϵ values of 940, 940, 1260, and 1190 M^{-1} cm^{-1} determined from reference samples or structurally similar compounds in our previous work.[5]

Norborneols and norbornyl acetates were determined by GC analysis on a 20% Carbowax column at 185 °C which separated the norborneols cleanly, with the exo isomer appearing first. In order to determine the exo–endo ratio of the acetates, we separated them by TLC using a Harrison Research Model 7924 Chromatotron (a device in which the chromatography is carried out on a spinning disk with solvent introduced at the center and collected at the periphery). Clean separation was achieved by using 20:1 CCl_4–ethyl acetate on silica gel. The acetates were hydrolyzed by being refluxed overnight with 20% NaOH, and the ratio of the resulting alcohols was determined by GC as above.

The acetate from the optically active *exo*-peroxide was isolated in the same manner, its purity checked by GC and spectra, and its optical rotation determined; $[\alpha]^{31}_D$ +0.775° (*c* 1.19, acetic acid). The literature gives $[\alpha]^{24}_D$ +14.20 (*c* 5.72, acetic acid) for pure material,[15] and the correlation of rotation and absolute configuration of the acid and alcohol has been established.[11]

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Registry No. *endo*-2-NorbornylC(O)OOC(O)C_6H_4-*m*-Cl, 79593-74-1; *exo*-2-norbornyl-C(O)OOC(O)C_6H_4-*m*-Cl, 79593-75-2; *cis*-4-*tert*-butylcyclohexyl-C(O)OOC(O)C_6H_4-*m*-Cl, 79593-76-3; *trans*-4-*tert*-butylcyclohexyl-C(O)OOC(O)C_6H_4-*m*-Cl, 79593-77-4; 2-butyl-C-(O)OOC(O)C_6H_4-*m*-Cl, 79593-78-5.

(10) If we wished to enter the long-standing controversy between the role of steric and charge-stabilizing effects in endo and exo solvolyses, since a bond between C-2 and a structurally similar OCO group is breaking here as well, the endo–exo difference we observe may be an upper limit to the steric contribution (since some charge is actually developing in our system as well).

(11) Berson, J. A.; Remanick, A. *J. Am. Chem. Soc.* **1964**, *86*, 1749–1755.

(12) Roberts, J. D.; Trumbull, E. R.; Bennette, W.; Armstrong, R. *J. Am. Chem. Soc.* **1950**, *72*, 3116–3124.

(13) Berson, J. A.; Walia, J. S.; Ramanick, A.; Suzuki, S.; Reynolds-Warnhoff, P.; Willner, D. *J. Am. Chem. Soc.* **1961**, *83*, 3986–3997.

(14) Berson, J. A.; Ben-Efraim, D. A. *J. Am. Chem. Soc.* **1959**, *81*, 4083–4087.

(15) Weinstein, S.; Trifan, D. *J. Am. Chem. Soc.* **1952**, *74*, 1147–1154.